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Latest Results from MINOS

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Amongst the goals of the MINOS experiment are the test of the $\nu_\mu \to \nu_\tau$ oscillation and the search for sub-dominant $\nu_\mu \to \nu_e$ oscillations. The former proceeds by a ν_μ "disappearance" analysis while the latter would involve the "appearance" of ν_e interactions in a predominantly ν_μ beam.

The disappearance of muon neutrinos is described by

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{23} L/E) \quad (1)$$

in the two-flavor approximation where θ_{23} is the angle between the second row and third column of the neutrino mixing matrix, $\Delta m^2_{23} = m^2_2 - m^2_3$ (eV^2), L is the neutrino flight distance in km and E is the neutrino energy in GeV. A generic disappearance experiment compares a measured muon neutrino energy spectrum at a fixed baseline to the known energy spectrum of muon neutrino beam to extract the oscillation parameters $\sin^2 2\theta$ which controls the overall magnitude of the disappearance and Δm^2 which controls the energy dependence.

MINOS is a long baseline neutrino experiment with a near detector (ND) located 1 km from the primary target in the Fermilab NuMI beam line and a far detector (FD) located 735 km away in the Soudan mine in Minnesota approximately 700 meters underground. To produce the neutrino beam, the 120 GeV main injector proton beam impinges upon a $\sim$1 m long segmented graphite target in a $\sim$10 μs spill. Two magnetic focusing horns downstream of the target focus positive mesons into the 675m long decay pipe where $\pi^+ \to \mu^+\nu_\mu$ decays are the dominant mechanism for the production of the neutrino beam. The NuMI target is moveable and the low energy (LE-10) configuration is the most favorable for the oscillation analysis and constitures $\sim$ 95% of the total exposure. The LE-10 beam is 92.9% ν_μ, 5.8% $\overline{\nu}_\mu$ and 1.3% $\nu_e + \overline{\nu}_e$. The remaining $\sim$5% of the exposure was taken with other configurations for systematic studies. For an exposure of 10^{20} protons-on-target (POT), approximately 390 ν_μ events are expected at the FD in the absence of oscillations.

Both the ND and FD are functionally identical and consist of 2.54 cm thick octagonal steel plates magnetized with a toroidal 1.2 T field interleaved with planes composed of 4.1 cm wide $\times$ 1 cm thick scintillator strips. Alternating U- and V-planes of scintillator are oriented at $\pm 45°$ with respect to the vertical. The ND and FD contains 282/152 and 484/484 steel/scintillator planes for a mass of 1 and 5.4 kt, respectively. The FD is divided into two equal length super modules.

Muon neutrino charged current (CC) interactions are identified by a long muon track and hadronic activity at the interaction vertex. By contrast, neutral current (NC) interactions often create short, diffuse showers whilst ν_e CC events are characterized by a typical compact electromagnetic shower profile. The neutrino energy is given by the sum of the shower and muon energy. The shower energy resolution is $55\%/\sqrt{(E \text{ GeV})}$ and the muon momentum resolution is 13% based on curvature and 6% based on range for muons that stop in the detector.

The separation of ν_μ CC candidates from the NC background begins with beam and data quality cuts (FD livetime $\approx 99\%$). Candidate events are required to have at least one negatively charged track with a vertex in the fiducial volume ($1 < z(\text{m}) < 5$ and $r(\text{m}) < 1$ at the ND and 0.5(2.0) meter from the front(rear) face of each FD supermodule and $r(\text{m}) < 3.7$). Further separation is provided by use of a 'particle identification' (PID) variable that combines three simulated probability density functions (PDFs) for CC and NC events. The three PDFs are the distribution of event length which is related to the muon momentum, the fraction of the pulse height in the event that is on the track which is related to the event inelasticity and the pulse height per plane on the track which is related to dE/dx. The resulting selection achieves a CC purity of $\sim$97% at both the ND and FD.

To predict the unoscillated FD energy spectrum, an extrapolation method is used that takes into account the two-body pion decay kinematics and the beamline geometry to accomodate the effective point (line) source of neutrinos as seen by the FD (ND). The primary extrapolation method is dubbed the 'beam matrix method' and it, as well as alternative methods, were tested extensively for robustness with simulated data.

Figure 1 shows the predicted FD ν_μ candidate spectrum using the matrix method as well as an alternative method and the data for a total exposure of 1.17×10^{20} POT. The oscillations parameters determined from the fit are $|\Delta m^2_{32}| = (2.74^{+0.44}_{-0.26}) \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{32} = 1.00^{+0.00}_{-0.13}$ where both the statistical and systematic uncertainties are included [1]. The results are compared to previous measurements in Figure 2 and show the improvement in $|\Delta m^2_{32}|$ precision achieved by the MINOS result. The systematic uncertainty is currently $\sim 40\%$ of the statistical uncertainty for $|\Delta m^2_{32}|$ and is largely data driven, thus it is expected to decrease with the accumulation of more data. Hence one expects the $|\Delta m^2_{32}|$ precision to be dominated by statistical uncertainty for the foreseeable future.

A ν_e "appearance" analysis by MINOS has a substantially different character than the disappearance analysis in that it is background dominated. The appearance

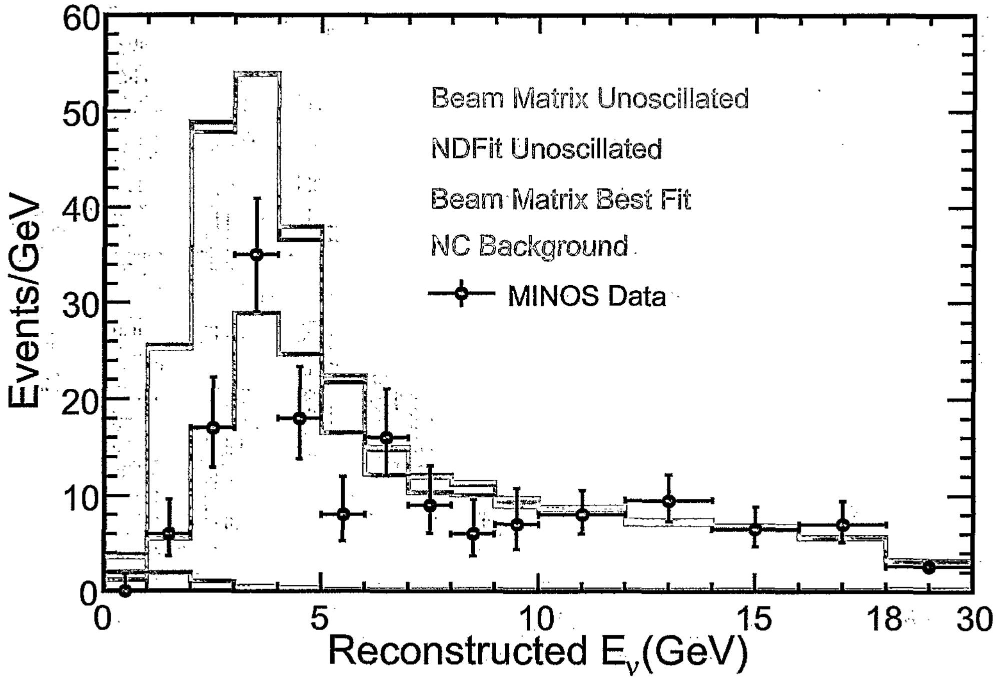

Figure 1: Comparison of the far detector spectrum with predictions for no oscillations for both analysis methods and for oscillations with the best-fit parameters from the beam matrix extrapolation method. The estimated NC background is also shown. The last energy bin contains events between 18-30 Gev.

probability is

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\Delta m^2_{23}L/E) \tag{2}$$

and is sensitive to $\sin^2 2\theta_{13}$ for which only an upper limit of 0.17 at 90% CL exists [3]. The ν_e appearance is difficult because the MINOS detector is not optimized for electromagnetic shower detection. Even with relatively sophisticated ν_e candidate selection, the background to signal ratio for $\sin^2 2\theta_{13} = 0.10$ is ≈ 2. Approximately 2/3 of the background is due to NC events where π^0 final states in the hadronic system produce electromagnetic showers. The intrinsic ν_e component of the beam is expected to contribute an additional $\sim 15\%$ of the background. The remaining two components each contribute $\sim 10\%$ and are due to ν_μ CC interactions with an unidentified muon track or to ν_τ CC events that have an electron in the final state.

Given that the ν_e appearance analysis is background-dominated, various techniques have been developed to estimate the background components from the data.

Two techniques are under investigation for estimating the NC background. One technique would create "NC" events by removing the reconstructed muon track from ν_μ CC events and reconstructing the "muon-removed" events. The second technique would use data with the magnetic horns turned off to resolve the NC and ν_μ CC background components at the ND. With the horns off, the high energy portion of the neutrino spectrum, which is largely responsible for the NC background, remains whilst the ν_μ CC component produced by the focusing of the horns, is greatly diminished (Figure 1). For the intrinsic ν_e beam component of the background, a technique that exploits the ability to MINOS to distinguish ν_μ and $\overline{\nu}_\mu$ is being investigated. The ν_e beam at low energy is dominated by ν_e from $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$ decays where the μ^+ are the produced by focused π^+ decays. The technique would attempt to resolve the $\sim$10% contribution to the $\overline{\nu}_\mu$ spectrum at the ND by subtracting the estimated contribution to $\overline{\nu}_\mu$ from pion and kaon decays. Assuming the total background can be determined with a $\pm$10% precision, MINOS can achieve a 90% CL sensitivity to $\sin^2 2\theta_{13}$ via ν_e appearance comparable to the current limit with an exposure of 4×10^{20} POT.

In summary, using an exposure of 1.27×10^{20} POT, MINOS has completed a ν_μ disappearance analysis with results $|\Delta m^2_{32}| = (2.74^{+0.44}_{-0.26}) \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{32} = 1.00^{+0.00}_{-0.13}$ consistent with previous results. Prospects for ν_e appearance analysis with the second year of running have been presented.

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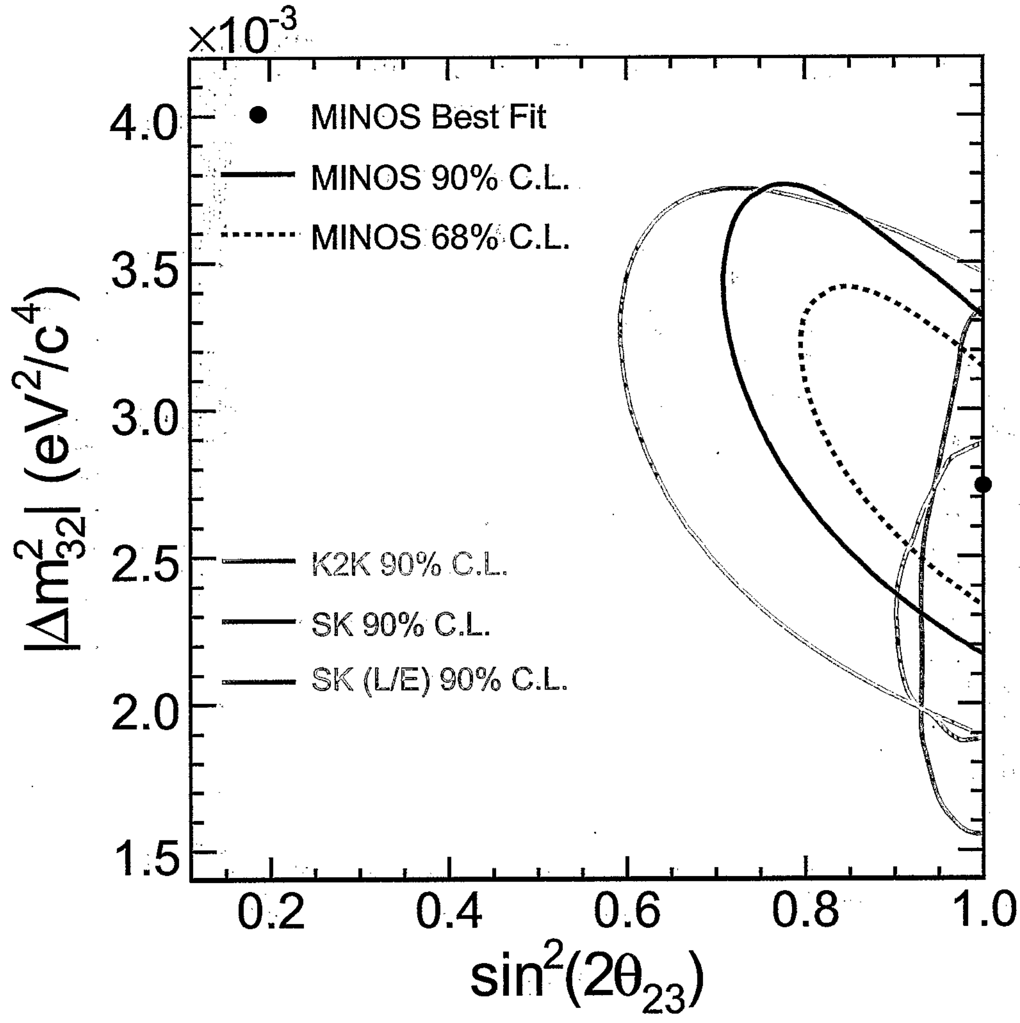

Figure 2: Confidence intervals for the fit to the MINOS data using the beam matrix method including systematic errors. Also shown are the contours from the previous highest precision experiments [2].